Impact Analysis of Wind Turbines Blockage on Doppler Weather Radar

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Abstract— **The split-step solution to the parabolic wave equation describing beam propagation permits examination of the signal degradation in a Doppler weather radar caused by wind turbines blockage under general atmospheric conditions and at arbitrary transmitter and receiver configurations. At radar wavelengths, an understanding of turbine and terrain obscuration effects is essential for deciding the reliability of radar measurements affected by blockage.**

I. Introduction

Even partial blockage of meteorological Doppler radar beams by any natural or man-made obstacle result in a deterioration of the radar performance and loss of sensitivity to atmospheric precipitation and wind conditions. In this respect, due to its high level radar cross sections and the rotation of its blades, wind turbines have a potentially strong impact on Doppler radar capacities. In many locations, the growing number of wind turbines close to those geographical elevated spots until now only occupied by weather radars, is becoming a serious threat to the reliability of radar meteorological measurements.

Wind turbines can impact coherent Doppler radars if they are within the radar's line of sight [1]. Within a few kilometers from the radar, they are close enough to partially block a significant percentage of the beam and attenuate signal down range of the wind turbine. They can also reflect energy back to radar and appear as clutter on the radar image and contaminate the base reflectivity data [2][3]. Finally, if the turbine blades are moving, they can impact the velocity and spectrum width data [4]. In this study, we focus our efforts in the analysis and quantification of blockage effects.

To analyze the effects of wind turbines blockage on coherent weather radar performance in a realistic way, it is necessary to consider the use of simulations of beam propagation in three-dimensional media. This study shows the viability of the split-step solution to simulate the propagation phenomena, establishing the limitations and numerical requirements for a simulation of given accuracy. Though the analysis shown in this paper is indebted to study blockage effects, the approach and conclusions of the propagation method are applicable to other areas dealing with wind turbines impact on coherent weather radars, i.e., clutter and spectrum effects. The authors anticipate addressing them in a following study.

II. Propagation and Analysis Techniques

The parabolic approximation to the wave equation and its split-step solution [5] has been used extensively in a variety of context to simulate propagation phenomena in both deterministic and random media (e.g., [6]-[8]). The split-step method offers a numerically efficient, full wave solution to the field because of the implementation of the Fast Fourier Transform (FFT) in a computer model. While computer execution times increase for increasing frequency and large propagation distances, with the availability of more powerful computing resources, such simulations have been extended to a variety of problems and there is an extensive body of applications of this technique to engineering problems.

Physically, the split-step technique corresponds to dividing the medium into slabs, each of which introduces a spatially varying contribution to the phase defined by the atmospheric refraction in the slab, and the radar wave beam is then propagated through a uniform medium from screen to screen. Although wavefront bends and radar beams are normally refracted downward towards the Earth, a curvature transformation is made that effectively maps the range-dependent terrain coordinate system to a flat or smooth earth coordinate system.

When the radar beam encounters an obstacle, i.e., terrain and wind turbines, power is removed from the beam and a radio shadow appears behind the obstacle. This occultation effect builds up by diffraction over many slabs and produces wave field distortions. Fields are numerically obtained at every propagation step, allowing detailed investigation of amplitude and phase distortions along the path. The radiation pattern of the radar antenna reveals an energy distribution into a complex lobe structure. Now, most of the energy may not be concentrated around the beam axis of the nominal radar antenna main lobe. It is of engineering interest to be able to predict the radiation pattern dependency, in the antenna and beam geometry, of wind turbine and terrain contributions to weather radar returns.

While plane waves are often a useful approximation, in many circumstances, in this analysis a more point like source which significant angular spread is required. This effect may be modelled by propagating in cylindrical or spherical coordinates. This approach, where the propagation medium is divided into spherical shells, keeps angular resolution constant. It allows us high resolution near the source and decreasing resolution with increasing sampling interval as the propagation distance increases.

III. Wind Turbine Blockage

In this analysis, we have considered typical modern horizontal-axis, three-bladed wind turbines used in wind farms for commercial production of electric power. The main rotor shaft and electrical generator is at the top of a tubular steel tower 80-m tall with a section expanding from 2 m at the top to 4 m at the base. Each of the blades connected to the shaft is 45-m length and 2-m broad. In our numerical analysis, we also include the effect of a supposedly flat, uniform terrain at the bottom of the turbine tower. As we intend to focus on wind turbine blockage alone, no other effects from terrain met by the radar beam before or after the turbine site are contemplated in the results presented in the paragraphs below.

In our estimations, and without loss of generality, we consider conventional C-band Doppler weather radars with 5.6-GHz operating frequency, 45-dB antenna gain, and 1.2-degrees half-power beam width. Other radar characteristics, such as pulse width, peak transmitted power, or receiver sensitivity, are not relevant to this blockage analysis. C-band weather radars send high-directional pulses of microwave radiation that spread out as they move away from the radar. At close ranges, radar pulses are just a few meters across and, consequently, they are prone to be block by obstacles in the proximity of the radar antennas. At far distances, the decreasing spatial resolution of the beams makes them less sensitive to blockage.

Figures 1 and 2 show the effects of wind turbines blockage on characteristic C-band Doppler weather radars. In these plots, we assume the slightly worst case scenario where the three turbine blades are visible to the radar. From Fig. 1, it is clear that wind turbines within a few kilometers of a meteorological radar can prevent the radar's beam from properly forming, thus causing significant radar estimation errors down range from the turbines. In this estimations, terrain and wind turbine occultation effects in the C-band weather radar antenna radiation pattern are shown when wind turbine was positioned 3-km away from the radar (upper plot) and the complex radiation structure (middle plot) was estimated 10-km down range from the turbine. As expected, this radiation pattern change considerably when the turbine is hit off-axis by the radar beam (lower plot).

As shown in Fig. 1, the number of spurious, secondary radiation lobes in the turbine-modified antenna radiation pattern is very large, in particular at short distances, and remains sufficiently significant even at large ranges down from the turbine. It may call into question the whole reliability of these radar measurements. In some applications, when low level signals in clear air conditions need to be measured, the radar system may be extremely affected by areas where the Doppler signal is distorted by the presence of near wind turbines.

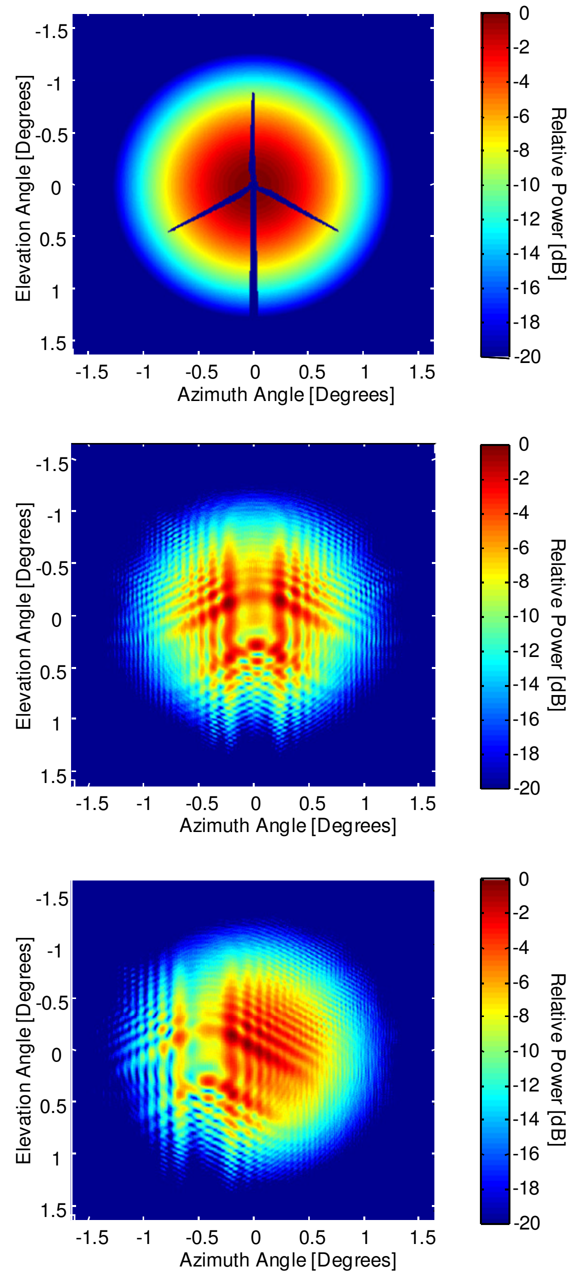

Fig. 1. Terrain and wind turbine occultation effects in a C-band weather radar antenna radiation pattern. In these simulations, wind turbine was positioned 3-km away from the radar (upper plot) and the complex radiation structure (middle plot) was estimated 10-km down range from the turbine. As expected, this radiation pattern change considerably when the turbine is hit off-axis by the radar beam (lower plot).

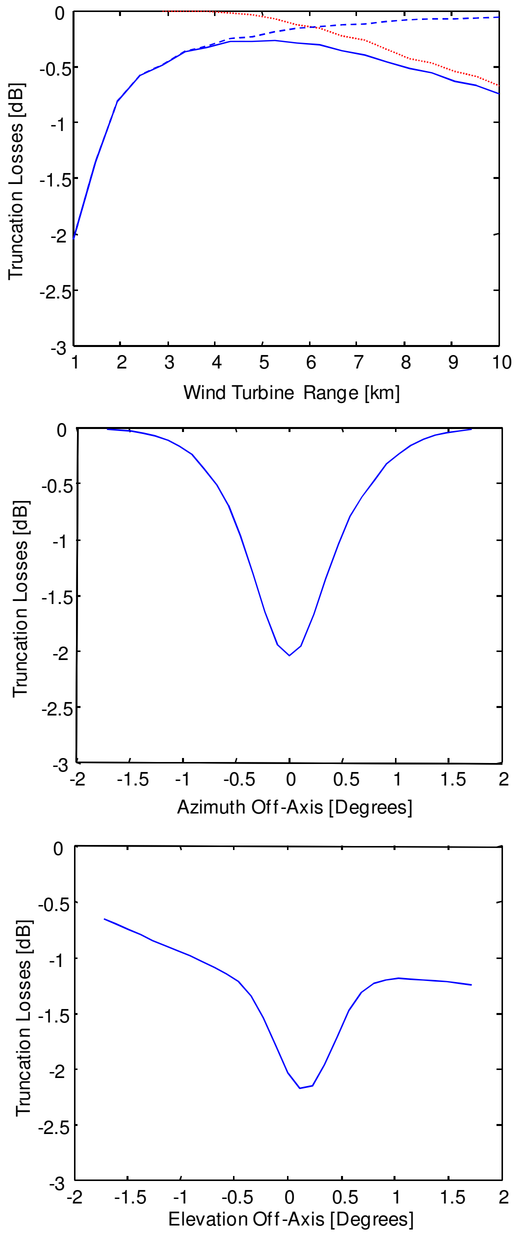

Fig. 2. Terrain and wind turbine occultation effects in a C-band weather radar. In the upper plot, terrain plus turbine truncation losses, in dB, are shown as a function of the separation between radar and turbine (solid blue line). We assume that the turbine is hit on-axis by the radar beam (see upper plot in Fig. 1). Terrain truncation losses (dotted red line) and wind turbine occultation losses (dashed blue line) are also shown separately. In the middle plot, for a 1-km away wind turbine, we plot occultation losses as a function of the azimuth off-axis beam impeding angle over the turbine. In the lower plot, for the same 1-km away wind turbine, we also plot occultation losses as a function of the elevation off-axis beam impeding angle.

In Fig. 2, occultation losses due to terrain and wind turbines are shown. Occultation may become an important attenuation contribution down range of the wind turbine. In the upper plot, terrain and wind turbine truncation losses, in dB, are shown as a function of the separation between radar and turbine (solid blue line). We assume that the turbine is hit on-axis by the radar beam, as shown in the upper plot of Fig. 1. Terrain truncation losses (dotted red line) and wind turbine occultation losses (dashed blue line) are also shown separately. In the middle plot, for a 1-km away wind turbine, we plot occultation losses as a function of the azimuth off-axis beam impeding angle over the turbine. In the lower plot, for the same 1-km away wind turbine, we also plot occultation losses as a function of the elevation off-axis beam impeding angle.

It thus appears that, in the case of the wind turbines analyzed in this study, the impact on the radar signal will be relevant at all azimuths and elevations for a turbine located up to 3 km away (Fig. 2, upper plot). As much as 2 dB truncation losses may be observed in any real Doppler radar working under such field-of-view restrictions. For wind turbine ranges beyond the 5-km mark, where the effects of terrain occultation are increasingly larger, turbine truncation can be adequately neglected. This situation is easily explained by the fact that, in general, at larger ranges, the turbine Doppler cross section is just a small fraction of the radar beam illuminated area. Now, the angular radar antenna discrimination is not large enough to be affected by distant wind turbines.

In the horizontal plane, taking into account the rotation of the radar, for wind turbine ranges up to 3 km, the values of impacted azimuths angles remain high, potentially blocking measurement on significant geographical areas (Fig.2, middle plot). For azimuth off-axis beam impeding angles several times the half-power beam width, the Doppler signal will undergo obscuration as far as the discrimination of the principal lobe of the antenna is within the direction of the wind turbine. Similar effects can be also noted in the vertical plane (lower plot in Fig. 2), where obscuration losses are shown in terms of elevation off-axis beam impeding angles. The lack of symmetry in the plot is associated to terrain effects (in the plot, positive off-axis beam elevation angles move the radar beam towards the terrain).

IV. Conclusions

To analyze the effects of wind turbines blockage on coherent weather radar performance in a realistic way, we have considered the use of simulations of beam propagation in three-dimensional media. The technique divides the medium into slabs, each of which introduces a spatially varying contribution to the phase defined by the atmospheric refraction, and the radar wave beam is then propagated through a uniform medium from screen to screen. When the radar beam encounters terrain and wind turbines, occultation effect builds up by diffraction over many slabs and produces a complex radiation lobe structure. The large number of spurious radiation lobes in the turbine-modified antenna radiation pattern may challenge the accuracy of radar measurements.

From our analysis, it results clear that wind turbines within 3 kilometers of a meteorological radar can prevent the radar's beam from correctly shaping and cause considerable radar estimation errors down range from the turbines. Our study seems to indicate that, even in simple case scenarios, where only one wind turbine is blocking the radar beam, obscuration losses may be in excess of 2 dB. The analysis of more complex, realistic situations, where several wind turbines in a wind farm may be in the radar line of sight at distances up to 10 km away, has also shown to produce a significant impact on the Doppler radar performance.

More detailed results and extended comments relative to our analysis will be presented at the meeting.

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